LYMAN ALPHA RADIATION IN EXTERNAL GALAXIES

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I. Introduction

The Lyα line of atomic hydrogen is often a luminous component of the radiation emitted by distant galaxies. Except for those galaxies which have a substantial central source of non-stellar ionizing radiation, most of the Lyα radiation emitted by galaxies is generated within regions of the interstellar medium which are photoionized by starlight. Conversely, much of the energy radiated by photoionized regions is carried by the Lyα line. Only hot, massive stars are capable of ionizing hydrogen in the interstellar medium which surrounds them, and because such stars are necessarily short-lived, Lyα emission traces regions of active star formation.

Observations of Lyα radiation - including indirect observations of the effects of such radiation upon the gas in which it is generated - may provide a valuable probe of the interstellar medium in star-forming regions of external galaxies; in the case of very distant galaxies Lyα observations may be almost the *only* such probe. Careful theoretical analysis is required to interpret these observations, because the transport of H Lyα photons is profoundly affected by the fact that in traversing an astrophysical medium such photons may suffer frequent absorption and resonant re-emission by hydrogen atoms in the ground state. Indeed, in escaping a neutral interstellar cloud of typical dimensions, H Lyα photons may suffer millions of resonant scatterings. The transfer of Lyα radiation in a highly opaque medium is thus a random walk process in which photons diffuse both in space and - by virtue of the velocity dispersion of the scattering H atoms - in frequency. Diffusion in frequency results in a broadening of the line profile: in traversing a medium of atomic column density $N(H^0)$, Lyα photons acquire a linewidth of 227 $(10^{-20}\text{cm}^2.N(H^0))^{1/3}\Delta v_5^{1/3}$ km s^{-1} FWHM, where Δv_5 km s^{-1} is the velocity dispersion of the scattering H atoms.

We argue that the *strength* of the Lyα emission observed from external galaxies may be used to estimate quantitatively the dust content of the emitting region, while the Lyα line *profile* is sensitive to the presence of shock waves. Interstellar dust particles and shock waves are intimately associated with the process of star formation in two senses. First, both dust particles and shock waves owe their existence to stellar activity; second, they may both serve as agents which facilitate the formation of stars, shocks by triggering gravitational instabilities in the interstellar gas that they compress, and dust by shielding star-forming molecular clouds from the ionizing and dissociative effects of external UV radiation. By using Lyα observations as a probe of the dust content in diffuse gas at high redshift, we might hope to learn about the earliest epochs of star formation.

Furthermore, the effects of Lyα radiation in selectively pumping warm H_2 molecules may be inferred from the in-frared spectrum of at least one external galaxy; such effects may serve as signpost of interstellar gas which has been heated and partially dissociated and ionized by X-rays.

II. Lyα as a probe of interstellar dust

In addition to being scattered, Lyα photons may be destroyed by dust absorption, a process which dominates the heating of dust in HII regions. Indeed, because of the extra path length that they must travel, Lyα photons are particularly vulnerable to attenuation by interstellar dust. The effects of such attenuation have been described quantitatively by numerical solution of the transfer equation (Hummer and Kunasz 1980), and recently (Neufeld 1989) by an extension of an analytic method due to Harrington (1973) in which the essential features of the radiative transfer process are described by a Poisson equation. Figure 1 shows the fraction of Lyα photons, f_e, which can escape from the center of a dusty interstellar slab.


Figure 1
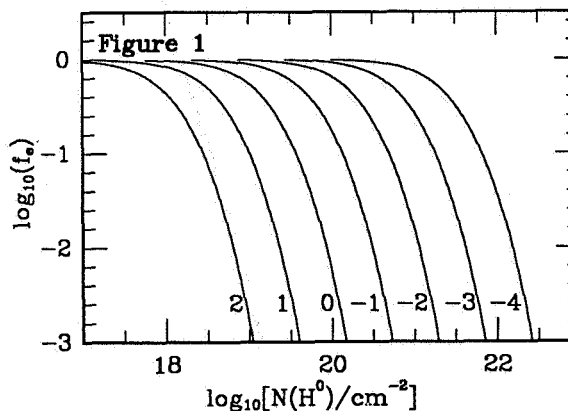
The horizontal axis gives the atomic column density $N(H^0)$ from the center of the cloud to its surface, and the different curves are labelled with the quantity $\log_{10}[\xi_d \Delta v_5^{-2/3} x(H^0)^{-1}]$, where $x(H^0)$ is the neutral atomic fraction, and ξ_d is the dust opacity per hydrogen nucleus, normalized relative to the standard Galactic value of Draine and Lee (1984).

In using observations of Lyα line strengths to estimate the dust content in an external galaxy, we require an estimate of the intrinsic, unattenuated luminosity. If the intrinsic equivalent width is known (from modelling of the stellar population), such an estimate may be derived from continuum measurements close to the Lyα wavelength. Alternatively, observations of Balmer or Brackett lines, or of free-free radio emission, might be used to determine the emission measure of the ionized gas. The distribution of ionized gas and of Lyα emission is also crucial.

Hartmann *et al.* (1988) have recently presented measurements of the Lyα/Hβ ratio in several Markarian galaxies

of redshift $z < 0.1$. The results are plotted in Figure 2 as a function of the estimated [O]/[H] ratio.

Figure 2
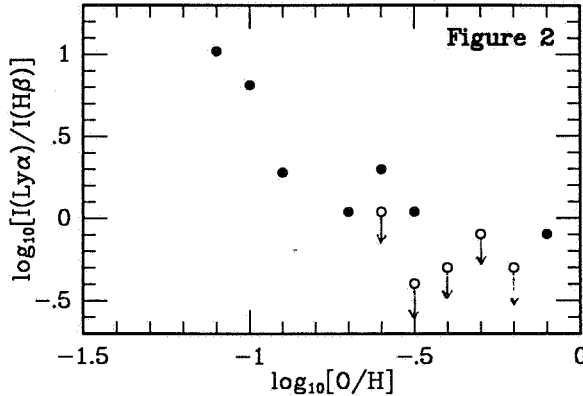
Without attenuation, the Lyα/Hβ ratio is expected from the theory of radiative recombination to lie around 20; the observed values range from about 1 (the detection limit in this data set) to about 10, presumably reflecting the fact that the resonantly scattered Lyα photons are far more vulnerable to dust absorption than the Hβ photons. Furthermore, the ratio tends to be larger in galaxies of low metallicity in which the dust content might be expected to be smaller.

We have computed the expected Lyα/Hβ ratio for the idealized case of a plane-parallel slab in which the neutral fraction, dust content, and recombination line emissivity are *constant*. The results are shown in Figure 3 for slabs of various surface-to-center column densities $N(H^0)$. The scattering H atoms are assumed to have a velocity dispersion of 10 km s^{-1}, and each curve is labelled with the value of $\log_{10}(N(H^0)/\text{cm}^{-2})$.

Figure 3
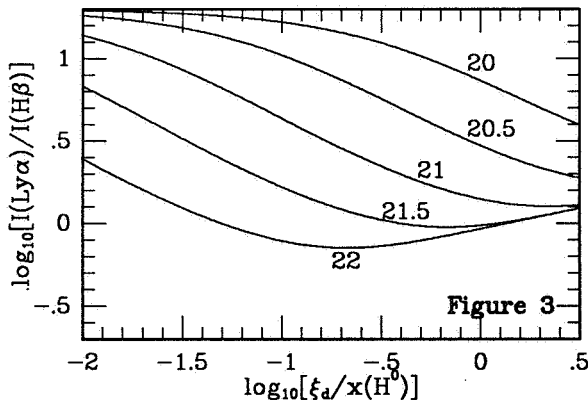
The ratio decreases with increasing $N(H^0)$ until the slab becomes optically thick for absorption both of Lyα photons and of Hβ photons. Further work is needed to treat the case where recombination line photons are generated within regions of low neutral fraction (HII regions) that are *embedded* in a medium of large neutral fraction (an interstellar cloud).

Measurements of the Lyα line *width* might in principle provide a further constraint upon the dust content of an emitting galaxy, since the line width yields an upper limit on the atomic column density through which a typical Lyα pho-

ton has travelled. For example, Hunstead and Pettini (1989) have recently reported the detection of a narrow emission line from the hydrogen cloud which gives rise to the $z=2.465$ damped Lyα line in the spectrum of the QSO 0836+113. The narrowness of the line (≤ 50 km s^{-1} FWHM) implies that the detected Lyα radiation has travelled through at most an atomic column of $(1 \times 10^{18}/\Delta v_5)$ cm^{-2}. However, the total column density through the cloud is known (from the absorption line it produces) to be 4.2×10^{20} cm^{-2}. Thus the Lyα emission is either generated close to the near surface of the cloud and nowhere else, or we are prevented from seeing embedded sources of radiation due to the effects of dust attenuation. A detailed quantitative analysis needs still to be carried out.

III.   Lyα as a probe of interstellar shocks

In considering the transfer of resonance-line radiation in a shocked interstellar cloud, we have found (Neufeld and McKee 1988) that the repeated scattering of Lyα radiation across a shock front results in a systematic blueshift which may greatly exceed the shock velocity. The blueshifting process is a first-order Fermi process analogous to that invoked to explain the acceleration of cosmic rays. When Lyα radiation is generated within a shocked cloud of neutral material the emergent line profile is given by: $\phi(v_b) \propto v_{b7}^2 \exp(-0.034 v_{b7}^3/v_{s7} N_{20})$, where $v_b = 100 v_{b7}$ km s^{-1} is blueshift relative to line center, $100 v_{s7}$ km s^{-1} is the shock velocity, and $N = 10^{20} N_{20}$ cm^{-2} is the column density of hydrogen atoms on either side of the shock front. The spectrum peaks at a blueshift $270(N_{20}v_{s7})^{1/3}$ km s^{-1}.

Fermi acceleration may be responsible for the blue asymmetric line profiles that have been observed in high redshift Lyα galaxies. The Lyα line profile in 3C326.1, measured by Djorgovski (1988), is shown in Figure 4.

Figure 4
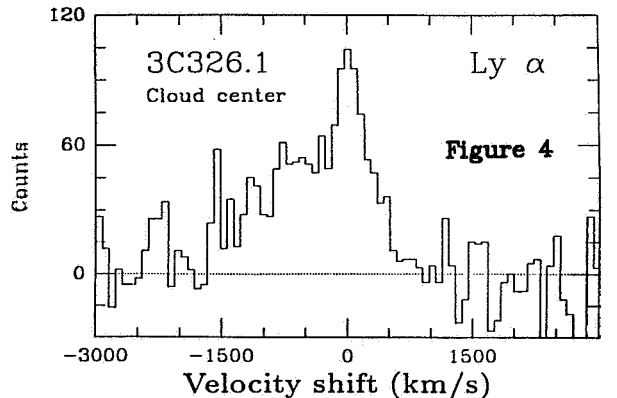
The observed spectrum may be accounted for quantitatively by a model in which shocks, driven into a population of interstellar clouds by a radio lobe, trigger the formation of ionizing stars and Fermi accelerate the Lyα radiation emitted by HII regions surrounding those stars. To match the observed line profile, which shows a blue wing extending to 2000 km s^{-1} from line center, the required pressure behind the shocks is 6×10^{-10} dyn cm^{-2}, consistent with a lower

limit on the pressure in the radio lobe that is set by the observed synchrotron emissivity. The shock velocity must lie between 10 and 400 km s^{-1} and the pre-shock density between 0.16 and 260 cm^{-3}. The virial temperature of the clouds is $\gtrsim 2 \times 10^4$ K, implying a line-of-sight velocity dispersion of at least 17 km s^{-1} for thermal or turbulent support. To allow the escape of Lyα radiation, the dust opacity per hydrogen atom must lie at least a factor 60 below the standard Galactic value. The absolute strength of the observed Lyα emission requires that the shocks trigger star formation with an efficiency greater than 0.5%.

A further consequence of the Fermi acceleration mechanism is that galaxy mergers, particularly between galaxies with low dust content, should produce Lyα lines with strong blue wings.

IV. H$_2$ pumping and the spectrum of NGC 6240

In warm gas containing H$_2$ in vibrationally-excited states, H Lyα radiation may pump coincident lines of the H$_2$ Lyman bands (Shull 1978, Black and van Dishoeck 1987), thereby being converted into ultraviolet fluorescent photons with a characteristic spectrum that has been observed both in sunspots (Jordan et al. 1977) and in Herbig-Haro objects (Brown et al. 1981; Schwartz 1983). There are two H$_2$ Lyman band transitions that lie close to the Lyα rest frequency: the B-X 1-2 R(6) transition (at a redshift of 15 km s^{-1} from line center) and the B-X 1-2 P(5) transition (at a redshift of 99 km s^{-1}.) The relative pumping rates in the two transitions may serve, in principle, as a probe of the Lyα line profile in the region of the warm H$_2$.

The pumping process may be treated *analytically* by methods described by Neufeld (1989). Figure 5 shows the fraction of Lyα photons, $(1 - f_e)$, which are converted into fluorescent photons of the Lyman bands before escaping from the center of a slab with a molecular fraction relative to H atoms of $x(H_2) \equiv n(H_2)/n(H^0)$. Each curve is labelled with the quantity $-\log_{10}x(H_2)$.

Figure 5

$\log_{10}[N(H^0)/cm^{-2}]$
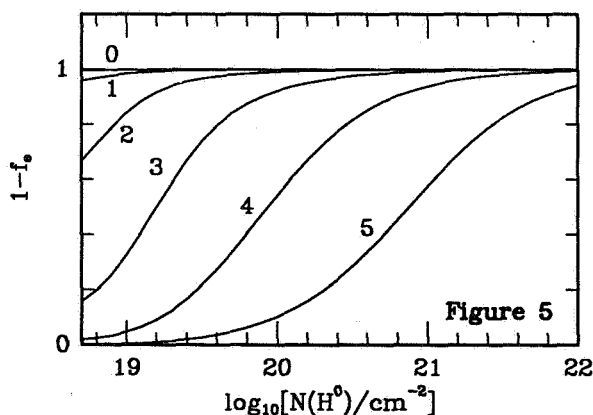
The results apply to a dust-free gas cloud at 4000 K in which the H$_2$ energy levels are thermally populated and the H atoms and H$_2$ molecules have a thermal velocity dispersion. Comparing Figures 1 and 5, we find that under these conditions, H$_2$ absorption dominates dust absorption when the molecular fraction exceeds about 10^{-4}. Figure 6 compares the total rate of pumping in the two transitions. The vertical axis shows the number of pumps in the B-X 1-2 P(5)

transition divided by the number in the B-X 1-2 R(6) transition.

Figure 6

$\langle[P(5)]/\langle[R(6)]$

$\log_{10}[n(H_2)/n(H^0)]$
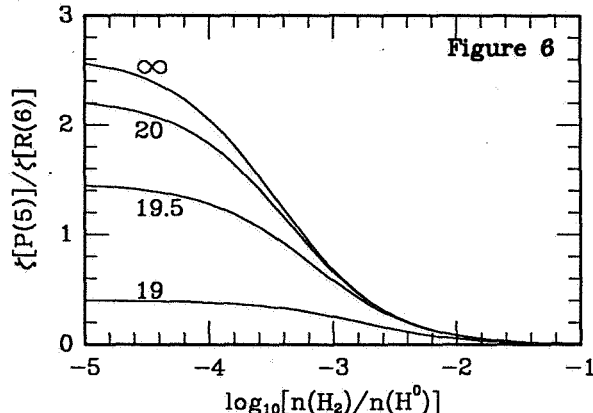
In addition to generating UV fluorescence, the pumping process may also modify the infrared emission spectrum of the warm, pumped H$_2$. For example, we expect the (v=2, J=5) and (v=2, J=6) states of H$_2$ to be selectively depopulated in regions of high Lyα flux. Such depopulation is the probable explanation of the anomalously small v=2-1 S(3) line intensity reported recently by Lester, Carr and Harvey (1988) for the starburst galaxy NGC 6240. (We might expect v=2-1 S(4) to be similarly diminished.) The required spatial coincidence of warm H$_2$ and Lyα emission may argue in favor of the model of Draine and Woods (1989), in which the copious H$_2$ rovibrational emission observed in NGC 6240 is produced in molecular clouds which are warmed, and partially ionized and dissociated by X-rays generated in a population of embedded supernova remnants. The expected diminution in the v=2-1 S(3) and v=2-1 S(4) line strengths is currently being investigated quantitatively by Neufeld, Draine and Woods.

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